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Development Report

TRANSIENT ELECTROMAGNETIC FIELDS NEAR A CYLINDRICAL ANTENNA MULTIPLY-LOADED WITH LUMPED RESISTORS

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ABSTRACT

The cylindrical antenna, driven at its center by some transient voltage input and symmetrically loaded with lumped resistors, has been found to be a useful electromagnetic pulse generator. In a previous study, a procedure was developed for selecting resistor pairs to be used to load the antenna. When these resistors are in place the radiated electromagnetic-field transient approximates some prescribed fast rising generally decaying function of time when a voltage step is impressed across the center terminals of the antenna.

In this report, the components of the transient electromagnetic field near the antenna are evaluated and the antenna synthesis procedure is extended to allow the selection of resistor pairs so that the magnetic field at a point of observation in the near zone approximates some prescribed transient waveshape.

Because this report is intended to be a supplement to the far-zone study, the same notation is used throughout the text and frequent reference is made to theory and equations developed in the previous study.

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Introduction

The primary use of the cylindrical antenna, multiply-loaded with lumped resistors, has been as an electromagnetic pulse generator for use in testing the effects of electromagnetic field transients on pieces of equipment that might be exposed to a transient field environment. In a recent study,[1] a synthesis procedure related to this problem was evolved. This synthesis procedure yields a selection of resistor pairs to be used to symmetrically load a cylindrical antenna so that the radiated electromagnetic field transient approximates some prescribed fast rising generally decaying function of time when a voltage step is impressed across the antenna terminals.

It may be desirable to conduct equipment tests near the radiating structure for one of the following reasons:

1. To obtain a high intensity pulse,
2. To simulate a monopolarity pulse,
3. To minimize the length of the required radiating antenna.

These advantages, gained by moving the test item in close to the structure, are not without cost; some of the more obvious and often undesired differences between near-field and far-field illumination of the test item are:

1. The spacial uniformity of the pulse is decreased. The incident field at one end of a test item is not exactly equal in amplitude or shape to that incident upon the other end.
2. The spacial distribution of the electric and magnetic fields are not identical, so that the $e_z(t)$ component is not merely 120π times the $h_\phi(t)$ component as it is in the far zone.

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[1] Merewether, D. E., "Transient Pulse Transmission Using Impedance Loaded Cylindrical Antennas," The University of New Mexico, Bureau of Engineering Research, EE149, February 1968.

3. In the near zone, the antenna also yields a $e_r(t)$ component that is not present in the far zone. This may result in an erroneous interpretation of test results taken on large items that may be significantly affected by both $e_r(t)$ and $e_z(t)$.

In this report, formulas are provided for the electromagnetic field components in the near zone. These formulas may be used to determine the variations in pulse shape and amplitude expected over the volume occupied by the item under test.

Also, the synthesis procedure (previously developed for the synthesis of far-zone electromagnetic field transients) that assumed a voltage step into the antenna has been extended to an arbitrary voltage input and a point of observation in the near zone. In the near zone, one may choose resistors so that $h_\phi(t)$ approximates some desired transient or so that $e_z(t)$ approximates some desired transient, but not both simultaneously. Selection criteria for either choice are given in the text of the report.

Analysis of Near-Zone Electromagnetic Fields

In this section, approximate formulas are developed for the transient electromagnetic fields observed near a cylindrical antenna multiply-loaded with resistors driven by a transient voltage source.

For the unloaded cylindrical antenna, of length 2h, symmetrically driven at points $z = \pm d$ by monochromatic voltage sources $V_d e^{+j\omega t}$ (Figure 1), the nonzero components of the electromagnetic field in cylindrical coordinates are

$$E_z(r, z) = -\frac{j\omega}{k_o^2}\left(\frac{\partial^2}{\partial z^2} + k_o^2\right)A_z(r, z) \quad (1)$$

$$E_r(r, z) = -\frac{j\omega}{k_o^2}\left(\frac{\partial^2}{\partial r \partial z}\right)A_z(r, z) , \quad (2)$$

$$H_\phi(r, z) = \frac{-1}{\mu_o}\frac{\partial A_z(r, z)}{\partial r} , \quad (3)$$

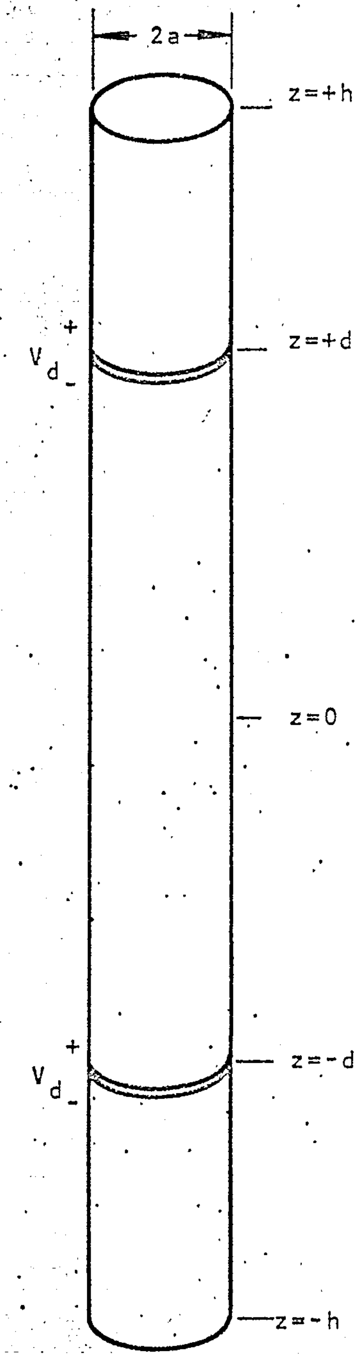

Figure 1. Idealized Symmetrically-Driven Antenna

where

$$A_z(r, z) \doteq \frac{\mu_o}{4\pi} \int_{-h}^{h} I(z', d) \frac{e^{-jk_oR}}{R} dz' , \tag{4}$$

and

$$R = \sqrt{r^2 + (z - z')^2} . \tag{5}$$

The approximate current distribution on the antenna was previously determined (3.11).[2]

$$I(z, d) = \frac{j2\pi V_d}{\psi Z_o \cos k_o h} \left[\sin k_o(h - |z - d|) + \sin k_o(h - |z + d|)\right] . \tag{6}$$

Substitution of the current distribution into the integral equation for $A_z(r, z)$ and performing the operations indicated in Equations (1), (2), and (3) yields

$$E_z(r, z) = - \frac{V_d}{\psi} \left\{ \frac{e^{-jk_oR_{1d}}}{R_{1d}} + \frac{e^{-jk_oR_{2d}}}{R_{2d}} - \frac{\cos k_o d}{\cos k_o h} \left[\frac{e^{-jk_oR_{1h}}}{R_{1h}} + \frac{e^{-jk_oR_{2h}}}{R_{2h}} \right] \right\} \tag{7}$$

$$E_r(r, z) = \frac{V_d}{\psi r} \left\{ \frac{(z - d)}{R_{1d}} e^{-jk_oR_{1d}} + \frac{(z + d)}{R_{2d}} e^{-jk_oR_{2d}} - \frac{\cos k_o d}{\cos k_o h} \left[\frac{(z - h)}{R_{1h}} e^{-jk_oR_{1h}} + \frac{(z + h)}{R_{2h}} e^{-jk_oR_{2h}} \right] \right\} \tag{8}$$

$$H_\phi(r, z) = \frac{V_d}{\psi Z_o r} \left\{ e^{-jk_oR_{1d}} + e^{-jk_oR_{2d}} - \frac{\cos k_o d}{\cos k_o h} \left[e^{-jk_oR_{1h}} + e^{-jk_oR_{2h}} \right] \right\} . \tag{9}$$

[2] The notation used here, (3.11), and similarly throughout the text refers to an equation number in the far-zone report cited as [1].

Here

$$R_{1d} = \sqrt{r^2 + (z - d)^2} \;, \qquad R_{2d} = \sqrt{r^2 + (z + d)^2} \;,$$

$$R_{1h} = \sqrt{r^2 + (z - h)^2} \;, \qquad R_{2h} = \sqrt{r^2 + (z + h)^2} \;.$$

Following the inverse Fourier transform procedures employed in the previous discussion of the far-zone field problem (Section 3.3), the components of the electromagnetic field observed when an arbitrary causal voltage is applied to the symmetrically loaded antenna are obtained in the form

$$e_z(r, z) = -\frac{1}{\psi}\left\{\frac{1}{R_o} v_o(t) + \sum_{i=1}^{N}\sum_{j=1}^{\infty} A_{i,j}\left[\frac{1}{R_{1d_i}} v_o\left(t - t_{1i} - 2(j-1)\Delta/c\right)\right.\right.$$
$$\left.\left. + \frac{1}{R_{2d_i}} v_o\left(t - t_{2i} - 2(j-1)\Delta/c\right)\right]\right\} \;, \tag{10}$$

$$e_r(r, z) = +\frac{1}{\psi r}\left\{\frac{z}{R_o} v_o(t) + \sum_{i=1}^{N}\sum_{j=1}^{\infty} A_{i,j}\left[\frac{(z - d_i)}{R_{1d_i}} v_o\left(t - t_{1i} - 2(j-1)\Delta/c\right)\right.\right.$$
$$\left.\left. + \frac{(z + d_i)}{R_{2d_i}} v_o\left(t - t_{2i} - 2(j-1)\Delta/c\right)\right]\right\} \tag{11}$$

$$h_\phi(r, z) = +\frac{1}{\psi Z_o r}\left\{v_o(t) + \sum_{i=1}^{N}\sum_{j=1}^{\infty} A_{i,j}\left[v_o\left(t - t_{1i} - 2(j-1)\Delta/c\right)\right.\right.$$
$$\left.\left. + v_o\left(t - t_{2i} - 2(j-1)\Delta/c\right)\right]\right\} \;. \tag{12}$$

All of the components are given in retarded time, where

$$R_o = \sqrt{r^2 + z^2}\ , \qquad R_{1d_i} = \sqrt{r^2 + (z - d_i)^2}\ , \qquad R_{2d_i} = \sqrt{r^2 + (z + d_i)^2}\ ,$$

and

$$t_{1i} = \left(d_i + R_{1d_i} - R_o\right)\Big/c\ , \qquad t_{2i} = \left(d_i + R_{2d_i} - R_o\right)\Big/c\ .$$

Equations (10), (11), and (12) are the desired description of the electromagnetic field near the radiating structure.

It may be noted that: at a point $(r, \phi, 0)$ the initial amplitude of the electric field is Z_o times the initial amplitude of the magnetic field, just as it is in the far zone. The subsequent shape of the pulse is different, however.

Transient-Voltage Input to the Antenna

In the synthesis procedure previously developed for far-zone fields, a voltage step was the assumed input to the antenna and a staircase approximation to the desired field transient was obtained. The procedure previously developed can be extended to any causal voltage source with only a slight modification. That is not to say that, given any arbitrary voltage transient input, the resistors may be chosen to yield some desired electromagnetic-field transient. However, if the desired field transient is within the class of functions that may be generated by the assumed voltage wave and a resistively loaded antenna, then the synthesis procedure will yield the required distribution of resistors.

The electric field observed at the point (Figure 2) $(r, \phi, 0)$ in the far zone is given by

$$e_z(r, 0) = -\frac{1}{\psi r}\left\{v_o(t) + 2\sum_{i=1}^{N}\sum_{j=1}^{\infty} A_{i,j}\, v_o\left(t - \left(i + 2(j - 1)\right)\Delta/c\right)\right\}\ , \qquad (13)$$

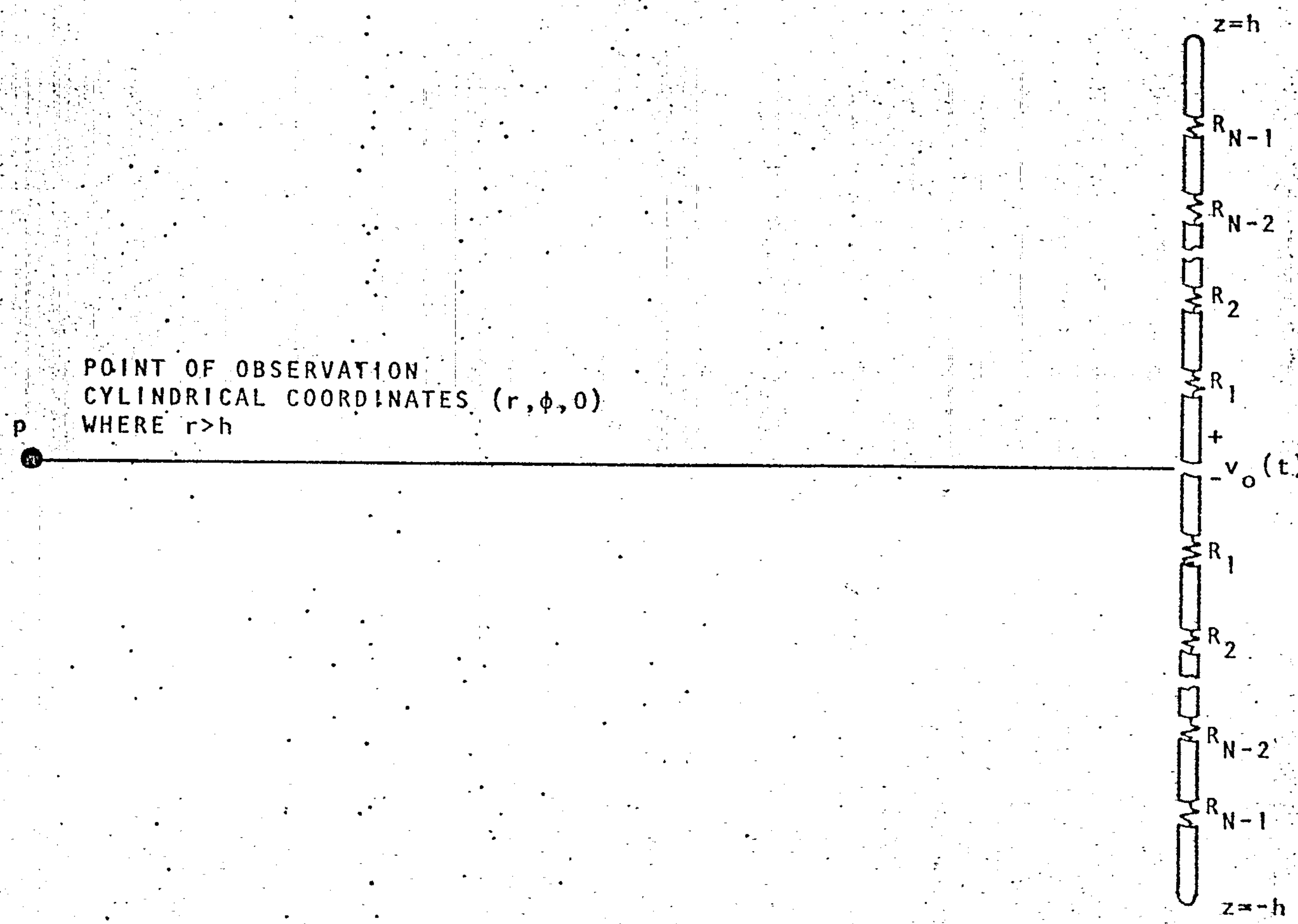

Figure 2. Multiply Loaded Antenna

in retarded time. Let $v_o(t)$ be some simple causal input of the form $v_o(t) = V_B f(t)$, where $f(0) = 0$, and $f(\Delta/c) = 1$. For this type of input the normalized far-zone electric-field transient is of the form

$$-\frac{\psi r e_z(r,0)}{V_B} = \left[f(t) + 2 \sum_{i=1}^{N} \sum_{j=1}^{\infty} A_{i,j} f\left(t - \left(i + 2(j - 1)\right)\Delta/c\right) \right] . \tag{14}$$

The synthesis proceeds by finding an approximate expansion of the desired normalized electric-field transient in the form

$$e_a(t) = \left[f(t) + \sum_{i=1}^{\infty} M_k f(t - k\Delta/c) \right] . \tag{15}$$

A solution for $A_{k,1}$ is then obtained by equating coefficients of $f(t - k\Delta/c)$:

$$A_{k,1} = M_k / 2 - \sum_{j=2}^{JM} A_{k-2(j-1),j} \quad , \quad k = 1, \ldots, (N-1) \quad , \tag{16}$$

and $JM = \text{Int}[(k + 1)/2]$. Int $[x]$ means the integral part of x. The required value of R_k is determined from (3.32).

The remaining question is how shall the M_k's be selected. In the previous development, the coefficient M_ℓ was selected so that the step approximation $e_a(t)$ yielded an average fit to the desired normalized electric-field transient $e_N(t)$ during the interval, $t_\ell < t < t_{\ell+1}$, where $t_\ell = \ell\Delta/c$. When the input is not a voltage step, this selection is not appropriate; several other methods of selection are possible, the easiest of which is to choose M_ℓ so that the approximation $e_a(t)$ is exactly equal to the desired normalized electric field $e_N(t)$ at $t = t_{\ell+1}$; here $e_N(t) \equiv e(t)/e(t_1)$.

$$e_N(t_{\ell+1}) = e_a(t_{\ell+1}) = f(t_{\ell+1}) + \sum_{k=1}^{\infty} M_k f(t_{\ell+1} - t_k) \quad , \tag{17}$$

since f(t) is causal, $f(t) = 0$ if $t < 0$, and since $f(0) = 0$, the desired value of M_ℓ is

$$M_\ell = \frac{e_N(t_{\ell+1}) - f(t_{\ell+1}) - \sum_{k=1}^{\ell-1} M_k f(t_{\ell+1} - t_k)}{f(t_{\ell+1} - t_\ell)} \tag{18}$$

The coefficients are obtained sequentially.

As a guideline of type of electric-field transient that may be generated by the resistively loaded antenna, it should be noted that the normalized waveshape observed is likely to be less than f(t), since the resistors have a degenerative effect on the field. Also it should be noted that, if the desired field waveshape is very similar to the applied voltage waveshape, the resistors would be small and a large reflection occurs when the wave reaches the end of the antenna.

Antenna Synthesis for Near-Zone Magnetic-Field Transients

In this section, a synthesis procedure is developed for selecting resistor pairs to be used to symmetrically load a cylindrical antenna so that the magnetic field observed at the point $(r, \phi, 0)$, in cylindrical coordinates, approximates some desired transient waveform. The restrictions that the point of observation is in the far zone and that the input voltage is a voltage step shall no longer be required.

If the applied voltage has the form $v_o(t) = V_B f(t)$ where $f(t_1) = 1$, and $f(t) = 0, t \le 0$, then the normalized magnetic field at the point of observation is obtained from (12).

$$\frac{\psi Z_o r h_\phi(r, 0)}{V_B} = \left\{ f(t) + 2 \sum_{i=1}^{N} \sum_{j=1}^{\infty} A_{i,j} f\left(t - t_i - 2(j-1)\Delta/c\right) \right\} \tag{19}$$

in retarded time, where

$$t_i = (i\Delta + R_{di} - r)/c$$

and

$$R_{di} = \sqrt{r^2 + (i\Delta)^2} \; .$$

When $r \gg h$, $t_i \doteq i\Delta$ and changes in the far-zone field occur periodically at intervals of Δ/c. Signal changes caused by higher order bounces between resistors near the center of the antenna arrive at the point of observation at the precise time that the signal caused by the passage of another resistor by the primary current wave arrives. The antenna designer has some control over every change in the radiated field.

When the point of observation is in the near zone, signal changes caused by multiple reflections between resistors arrive at the point of observation between the times that correspond to the arrival of the primary wave at another resistor, because of the differences in signal time delay. Since the designer may exercise control over the waveform only when the primary wave passes another resistor, a somewhat degraded waveform can be expected. For this case, the synthesis proceeds by finding an approximation to the desired magnetic field in the form

$$h_a(t) = f(t) + \sum_{k=1}^{\infty} M_k f(t - t_k) \; . \tag{20}$$

Here $t_k = (k\Delta + R_{dk} - r)/c$ and M_k is determined by (18) exactly as it is in the far-zone case. An equation for $A_{\ell,1}$ from which R_ℓ may be determined by equating (19), the field produced by the antenna, to (20), the approximation of the desired field at time $t = t_{\ell+1}$ for $\ell < N$.

$$\sum_{k=1}^{\ell} M_k f(t_{\ell+1} - t_k) = \sum_{i=1}^{\ell} \sum_{j=1}^{JU} A_{i,j} f\left(t_{\ell+1} - t_i - 2(j-1)\Delta/c\right) \; . \tag{21}$$

Here the condition imposed upon f, that $f(t) = 0$ for all $t \geq 0$, has been employed to reduce the infinite summations to tractable summations:

$$JU = \text{Int}\left[c(t_{\ell+1} - t_i)/2\Delta + 1\right] \quad . \tag{22}$$

$A_{\ell,1}$ occurs in (21) in more than one place; the selection of R_ℓ also influences the value of the higher order reflections from resistors closer to the center of the antenna. Because of time-of-flight considerations, these reflections may arrive at the point of observation before $t_{\ell+1}$. In Figure 3, the point z_e on the antenna represents the point where the travel time from $\ell\Delta$ to z_e to the point of observation is exactly equal to the travel time from $\ell\Delta$ to $(\ell + 1)\Delta$ to the point of observation. The point z_e lies between $-\Delta$ and $(\ell - 1)\Delta$, which are the limits for $r = 0$ and $r = \infty$, respectively. The exact value is obtained from (23) below.

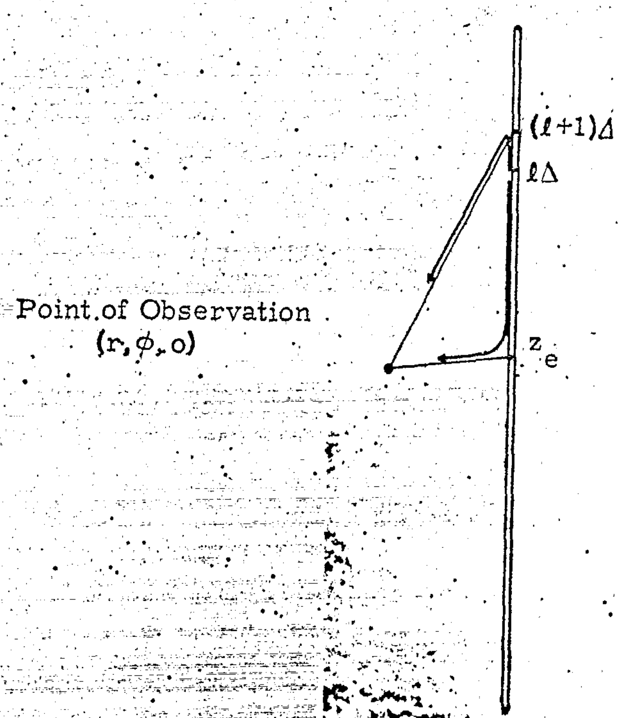

Figure 3. Travel Time Comparison

$$z_e = \frac{r^2 - D^2}{2D} \,, \qquad 0 < r < \infty \,, \tag{23}$$

where $D = \sqrt{r^2 + (\ell + 1)^2\Delta^2} - (\ell - 1)\Delta$. Higher order bounces from resistors located above point z_e involve $A_{\ell,1}$ and arrive at the point of observation before $t = t_{\ell+1}$. When the total contribution of $A_{\ell,1}$ is factored from Equation (21), the form below is obtained.

$$\sum_{k=1}^{\ell} M_k f(t_{\ell+1} - t_k) = 2 \sum_{i=1}^{\ell} \sum_{j=1}^{JU} A_{i,j} f\left(t_{\ell+1} - t_i - 2(j-1)\Delta/c\right)\Bigg|_{A_{\ell,1} = 0}$$

$$+ 2A_{\ell,1} \sum_{j=1}^{\ell - IU} C(j) f\left(t_{\ell+1} - t_{\ell+1-j} - 2(j-1)\Delta/c\right) \,, \tag{24}$$

where

$$IU = \mathrm{Int}\left[z_e/\Delta\right] \,,$$

$$C(1) = 1 \,,$$

$$C(j) = \Gamma_{\ell+1-j} \sum_{m=1}^{j-1} C(m) \,, \quad j > 1$$

and

$$\Gamma_{\ell+1-j} = \frac{-R_{\ell+1-j}}{R_{\ell+1-j} + Z_A} \,.$$

Solving for $A_{\ell,1}$

$$A_{\ell,1} = \frac{\sum_{k=1}^{\ell}\left\{M_k f(t_{\ell+1} - t_k) - 2\sum_{j=1}^{JU} A_{k,j} f\left(t_{\ell+1} - t_k - 2(j-1)\Delta/c\right)\Big|_{A_{\ell,1}=0}\right\}}{2\sum_{j=1}^{\ell-IU} C(j) f\left(t_{\ell+1} - t_{\ell+1-j} - 2(j-1)\Delta/c\right)} \quad (25)$$

If the desired values of $A_{\ell,1}$ are determined sequentially, the required value of R_ℓ may be determined from Equation (3.32) in the far-zone study. The selection of $A_{\ell,1}$ is essentially the end of the synthesis problem for near-zone magnetic fields. An equivalent formula for the synthesis of the z-component of the electric field may also be obtained in the same manner; the result is

$$A_{\ell,1} = \frac{\sum_{k=1}^{\ell}\left\{M_k f(t_{\ell+1} - t_k) - 2\sum_{j=1}^{JU} A_{k,j} \frac{r}{R_{dk}} f\left(t_{\ell+1} - t_k - 2(j-1)\Delta/c\right)\Big|_{A_{\ell,1}=0}\right\}}{2\sum_{j=1}^{\ell-IU} C(j) \frac{r}{R_{d\ell+1-j}} f\left(t_{\ell+1} - t_{\ell+1-j} - 2(j-1)\Delta/c\right)} \quad (26)$$

where the approximate shape of the desired electric field is

$$e_a(t) = f(t) + \sum_{k=1}^{\infty} M_k f(t - t_k) \quad (27)$$

As in the far-zone case, the antenna designer loses control of the radiated waveshape when the primary wave of current reaches the end of the antenna. The length of the antenna must be chosen so that most of the desired waveshape has been simulated when the primary wave reaches the end of the antenna. As an example of the effect of truncating the antenna on the resultant magnetic-field transient, the desired waveshape,

$$h(t) = e^{-t/T}, \quad (28)$$

was considered. The spacing between resistors was chosen to be

$$\Delta = cT/12.5 \ . \tag{29}$$

It was assumed that the voltage input to the antenna was a voltage step and that the synthesis range was 3Δ. Antennas with half-lengths 14Δ, 10Δ, and 6Δ were considered. Figure 4 shows the normalized magnetic field at the point of observation produced by each of the antennas. The portion of the waveform that is of interest here is the portion after $t = (h + R_h - r)/c$, $R_h = \sqrt{h^2 + r^2}$; this is the portion the designer has no control over; the current wave has reached the end of the antenna and the subsequent waveform is controlled entirely by the previous choice of resistors. For the longest antenna, the reflection from the end of the antenna is apparent at t = 2.02T; the gradual decay of the magnetic field after this time is not too dissimilar from the desired waveform. As the antenna is shortened, less of the desired waveform is generated before the wave reaches the end of the antenna, and a larger current wave approaches the end of the structure. Accordingly, the change in the magnetic field caused by reflection from the end of the antenna is larger, and a poorer over-all approximation results.

In Figure 5, the normalized electric field for each of these three antennas is exhibited. These waveforms all approach a static dc value because the point of observation is well within the "static zone" of the antenna. For a voltage step type of input, an estimate of the final value of the observed electric field may be obtained from the zero frequency limit of the electric field produced by an unloaded antenna center driven by a monochromatic voltage source,

$$E_{static} = \lim_{\omega \to 0} E_z(r, 0) = \lim_{k_o \to 0} \left\{ - \frac{V_o}{\psi} \left[\frac{e^{-jk_o r}}{r} - \frac{1}{\cos k_o h} \frac{e^{-jk_o R_h}}{R_h} \right] \right\} . \tag{30}$$

Here

$$R_h = \sqrt{r^2 + h^2} \ .$$

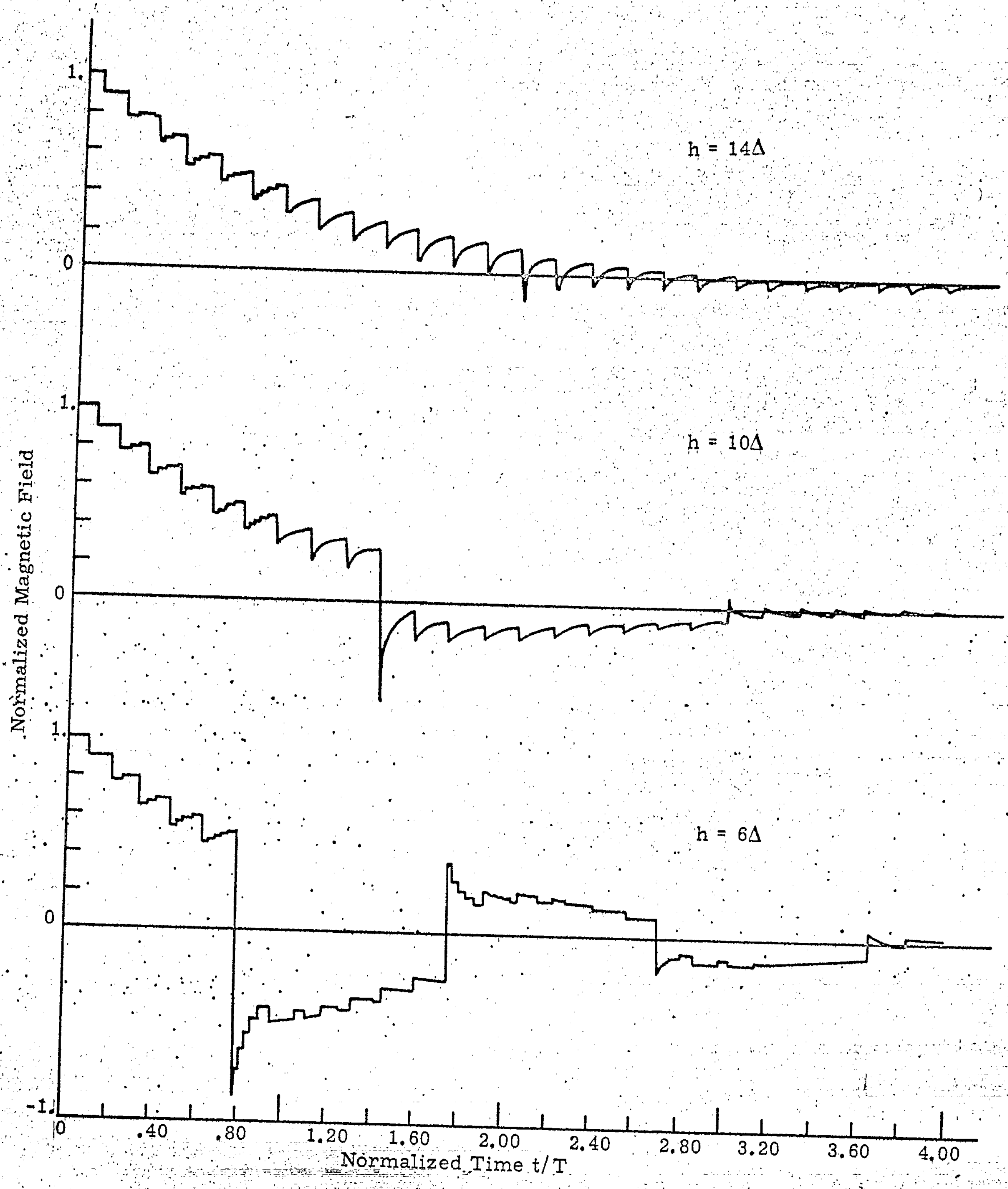

Figure 4. The Effect of Truncating the Antenna on the Observed Magnetic Field Waveshape at $r = 3\Delta$

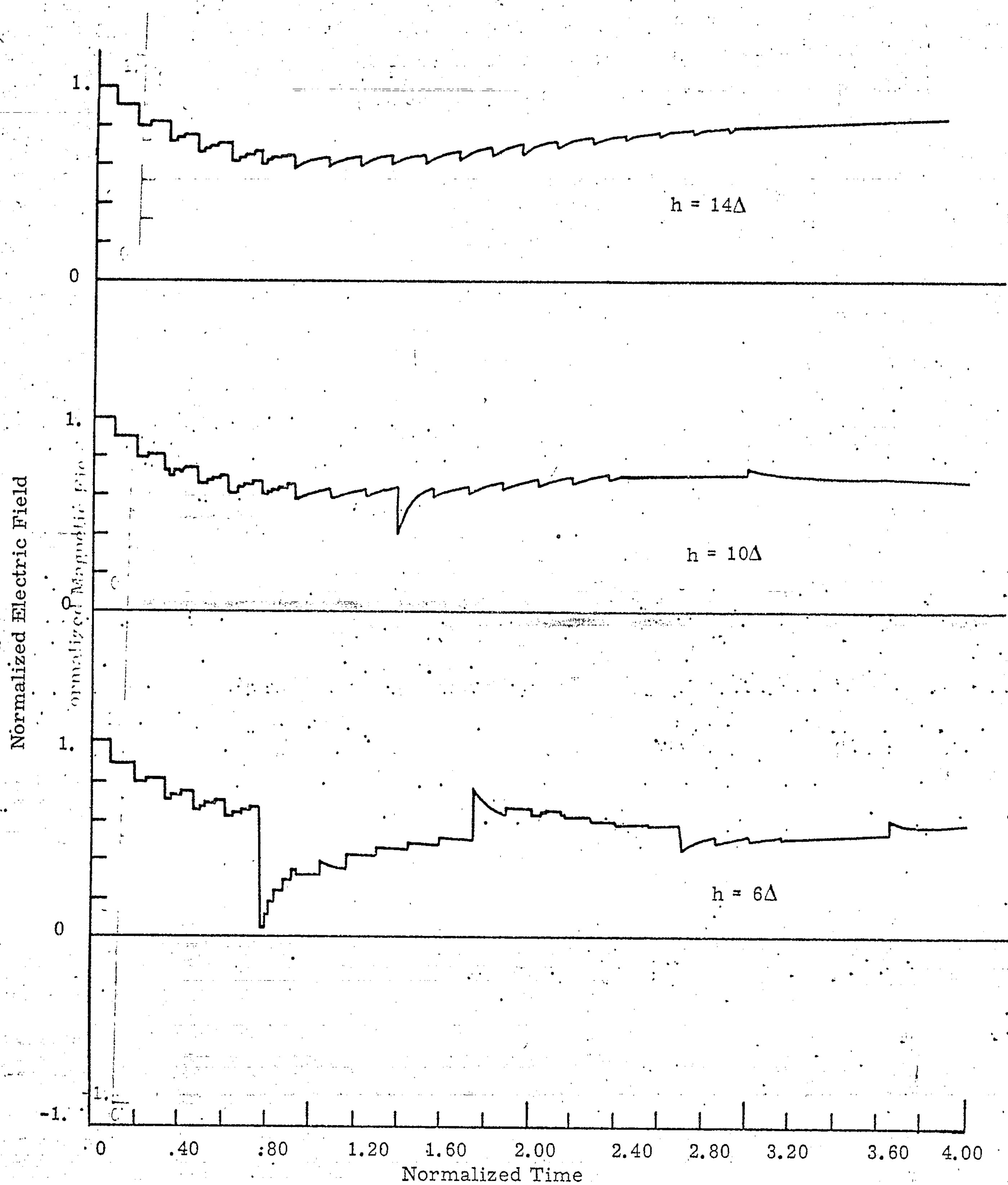

Figure 5. The Effect of Truncating the Antenna on the Observed Electric Field Waveshape r = 3Δ

Only an unloaded antenna need be considered because, in the low-frequency limit, there is no current flowing on the antenna and consequently no voltage developed across the resistors. Evaluating (30) we have

$$E_{static} = - \frac{V_o}{\psi}\left[\frac{1}{r} - \frac{1}{R_h}\right] \quad (31)$$

where V_o is the final value of the applied voltage. If $v_o(t)$ is a voltage step then the percentage of the initial peak field that is retained as a static component is

$$\%_{static} = \frac{-\frac{V_o}{\psi}\left[\frac{1}{r} - \frac{1}{R_h}\right]}{-\frac{V_o}{\psi r}} \times 100 ,$$

$$\%_{static} = 100 \times \left[1 - \frac{r}{R_h}\right] . \quad (32)$$

This static component could be eliminated by using an input voltage transient that eventually goes to zero; however, the static component is not a very serious consideration since very few pieces of electronic apparatus will respond to a static electric field.

The sharp discontinuities that occur in the waveforms shown in Figures (4) and (5) are primarily associated with the assumed zero rise time on the exciting step. If a voltage step type of waveform with a nonzero rise time is employed, a smoother approximation results.

Limitations of the Analysis

The primary limitation of the simplified antenna theory that the analysis is based upon is the requirement that the radius of the antenna is small enough that the "characteristic impedance" Z_a of the antenna may be considered to be a frequency independent constant. According to the simplified theory, when a voltage source is impressed across the input terminals of the antenna, the initial input current is a pulse of identical shape given by

$$i_{in}(t) = \frac{v_{in}(t)}{Z_a} .$$

For thin antennas, where the radius of the antenna is small compared to the wavelength of the highest significant frequency of the pulse, this response is an excellent approximation of the effect actually observed in the laboratory, and very good quantitative results can be expected from the use of the simplified theory.

For thicker antennas, current rapidly rushes onto the structure to charge up the capacity in the neighborhood of the drive terminals so that, if the input voltage is a voltage step, the input current has a significant spike on the front of the waveform and the "characteristic impedance," Z_a, cannot be considered to be frequency independent. Use of the simplified theory can only yield a qualitative picture of the transient response of a thick antenna. For the antenna synthesis problem, the use of a thin antenna is certainly desirable, for then the synthesis procedure will yield the desired resistor values with reasonable accuracy. However, structural considerations and driving voltage conditions may require the use of a thick antenna. When a thick antenna must be used, the synthesis procedure can only provide an initial selection of resistors; final adjustment of the values experimentally must be anticipated.

In the Section entitled "Antenna Synthesis for Near-Zone Magnetic-Field Transients," formulas for the selection of the values of the resistor pairs used to symmetrically load the antenna were based upon the synthesis of either a desired magnetic-field transient or a desired electric-field transient at the point of observation in the near zone. It should be noted, however, that the electric field near the antenna has a static component so that the synthesis of an electric-field transient that has no static component cannot be accomplished with a voltage step into the antenna. For this type of input voltage, the magnetic field is more easily handled.

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